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RESEARCH MEMORANDUM

A FLIGHT STUDY OF THE EFFECTS ON TRACKING PERFORMANCE OF CHANGES IN THE LATERAL-OSCILLATORY CHARACTERISTICS OF A FIGHTER AIRPLANE

By Walter E. McNeill, Fred J. Drinkwater III,
and Rudolph D. Van Dyke, Jr.

Ames Aeronautical Laboratory
Moffett Field, Calif.

NATIONAL ADVISORY COMMITTEE
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SUMMARY

A conventional, propeller-driven fighter airplane equipped with servo devices for varying in flight the lateral-oscillation period, damping, and roll-coupling parameter has been used in an investigation of the effects of these characteristics on fixed-sight tracking performance in selected air-to-air gunnery maneuvers consisting of straight tail chases followed by 2g or 3g target evasive turns.

Results are presented in the form of standard deviation of tracking error in yaw and pitch as functions of period, damping, and roll coupling in steady 1g flight and in 2g and 3g target turns for two pilots in smooth air and for one pilot in simulated rough air. Tracking-performance characteristics during the transition from straight flight to steady turns are presented as yaw-error bias and standard deviation.

In smooth air, some differences in tracking performance were measured as the lateral-oscillatory characteristics were varied, with standard deviation of yaw tracking error in straight flight and in steady turns varying from 1.2 mils to 3.6 mils. However, these values were small and the differences measured were considered insignificant. In the event of future improvement in other factors affecting hit probability, especially ballistic dispersion, these differences may become significant.

In simulated rough air, standard deviation of tracking error in yaw σ_x increased as the lateral period and damping were reduced. For example, σ_x increased from 2.4 mils to 8.3 mils as period P and damping $1/C_{1/2}$ were varied from 4.5 to 2.3 seconds and from 2.1 to 0.20, respectively. It appears that desirable rough-air tracking performance can be attained most effectively by assuring that the lateral oscillation is well damped, particularly at short periods.

INTRODUCTION

The Ames Aeronautical Laboratory has previously studied the effects of wide variations in the lateral-oscillatory characteristics on pilots' opinions of the flying qualities of a conventional, propeller-driven fighter airplane (ref. 1). In addition to these pilots' opinions, which are based to a large extent on ease and comfort of flight, quantitative measurements of the effects on the ability to control the airplane precisely are also of importance.

Accordingly, the Ames Aeronautical Laboratory has continued this investigation by studying the effects of changes in the period, damping, and roll-to-yaw ratio in controls-fixed lateral oscillations on air-to-air fixed-sight tracking performance in selected flight maneuvers. The variable-stability test vehicle described in reference 1 was employed in this study.

Related NACA flight investigations concerned with fixed-sight tracking performance are reported in references 2, 3, and 4.

NOTATION

A_{Z_a} normal acceleration of tracker, g units

ΔA_{Z_a} average change in tracker normal acceleration during target turn-reversal maneuver, $\frac{\Sigma \Delta A_{Z_{a_i}}}{n}$, g units

A_{Z_t} normal acceleration of target, g units

$C_{1/2}$ number of cycles required for lateral oscillation to damp to half amplitude, $\frac{T_{1/2}}{P}$

C_2 number of cycles required for lateral oscillation to double amplitude

g acceleration of gravity, 32.2 ft/sec^2

n number of observations

P period of lateral oscillation, sec

R_o initial range, ft

r_t target turn radius, ft

$T_{1/2}$ time for lateral oscillation to damp to half amplitude, sec

T_{A_Z} time required for normal acceleration of tracker to increase from 1g to steady-turn value, sec

V true airspeed, ft/sec

v_e equivalent side velocity, $\beta V\left(\frac{\rho}{\rho_o}\right)^{1/2}$, ft/sec

x instantaneous tracking error in yaw, mils

$\bar{x}$ mean tracking error in yaw, $\frac{\Sigma x}{n}$, mils

y instantaneous tracking error in pitch, mils

$\bar{y}$ mean tracking error in pitch, $\frac{\Sigma y}{n}$, mils

β angle of sideslip, radians

$\frac{\rho}{\rho_o}$ ratio of standard air density at test altitude to standard air density at sea level

σ_x standard deviation of tracking error in yaw, $\sqrt{\frac{\Sigma(x-\bar{x})^2}{n}}$, mils

σ_y standard deviation of tracking error in pitch, $\sqrt{\frac{\Sigma(y-\bar{y})^2}{n}}$, mils

σ_ψ standard deviation of yaw angle in controls-fixed simulated rough-air runs, $\sqrt{\frac{\Sigma(\psi-\bar{\psi})^2}{n}}$, mils

τ average time between reversals in target turn-reversal maneuver, $\frac{\Sigma\tau_i}{n}$, sec

$\frac{|\varphi|}{|v_e|}$ ratio of bank-angle amplitude to equivalent side-velocity amplitude in the oscillatory mode, $\frac{\text{degrees}}{\text{ft/sec}}$

$\dot{\varphi}$ rolling velocity, radians/sec

$\Phi_{\dot{\varphi}}$ power spectral density of rolling velocity, $\frac{\text{radians}^2/\text{sec}^2}{\text{cps}}$

$\Phi_{\dot{\psi}}$ power spectral density of yawing velocity, $\frac{\text{radians}^2/\text{sec}^2}{\text{cps}}$

ψ angle of yaw, mils

$\bar{\psi}$ mean angle of yaw, $\frac{\Sigma\psi}{n}$, mils

$\dot{\psi}$ yawing velocity, radians/sec

EQUIPMENT AND INSTRUMENTATION

Test Airplane and Servo Apparatus

A photograph of the test airplane is shown in figure 1.

The apparatus for varying the dihedral effect through servo actuation of the ailerons is described in reference 5 and the apparatus for varying static directional stability and yaw damping through servo actuation of the rudder is described in reference 1. For the present tests, provisions also were made for servo actuation of ailerons and rudder proportional to rolling velocity. This allowed variations of damping in roll and yawing moment due to rolling velocity.

Rough-Air Simulator

The effects of rough air on the lateral behavior of the airplane were simulated by a device which furnished additional signals to the aileron and rudder servos. These signals were controlled by cams, similar to those used in a Link trainer, to provide random disturbances through the ailerons and rudder. The amplitude of the aileron and rudder servo signals and the cam speed were variable in flight, providing repeatable simulation of a wide range of rough-air conditions.

Gunsight and Camera

A lead-computing sight unit (U.S. Navy Bureau of Ordnance Mark 8, Mod 0) was installed in the airplane as shown in figure 2. Only the fixed reticle was used in these tests. A GSAP camera with a three-inch focal-length lens was mounted on the sight head and photographed the target airplane with color film at 16 frames per second through a right angle adapter. Since the fixed reticle was not photographed by the camera, cross hairs were mounted in the camera focal plane to serve as a reference for measuring tracking errors. The camera was then boresighted with the fixed pipper on a distant aiming point; however, since it was extremely difficult to bring the intersection of the camera cross hairs exactly into alinement with the pipper, small instrument bias errors, which later were extracted from the tracking-error data, were introduced.

Instrumentation

In addition to yaw and pitch tracking errors, the following quantities were measured during each tracking run: yawing velocity, rolling velocity, normal acceleration, sideslip angle, indicated airspeed, pressure altitude, rudder servo position, aileron servo position, pilot-applied rudder deflection, and pilot-applied aileron deflection. These quantities were recorded by standard NACA recording instruments synchronized by a 0.1-second instrument timer. Time correlation between the 16-mm gun-camera film and the flight records was furnished by applying separate marks to the gun-camera film and to the sideslip record at one-frame and six-frame intervals.

FLIGHT TECHNIQUE AND DATA REDUCTION

Lateral-Oscillatory Characteristics Investigated

In order to observe gross effects on tracking performance of variations in lateral period P, damping $1/C_{1/2}$, and roll coupling $|\varphi|/|v_e|$, reasonably wide ranges of these characteristics were investigated. Five combinations of P, $1/C_{1/2}$, and $|\varphi|/|v_e|$ (henceforth referred to as configurations) were chosen and are presented in table I along with average values of standard deviation of yaw tracking error σ_x for both pilots in straight flight and in 2g and 3g turns. These five configurations are plotted in terms of period and time to damp to half amplitude in figure 3 to show their relationships with the current Armed Services specifications of references 6 and 7. Figure 4 shows a comparison of the five configurations with the pilot-opinion boundaries of reference 1.

Tracking Maneuvers

The tracking flights were conducted at 200-knots indicated airspeed and 7000-feet pressure altitude. A propeller-driven fighter airplane of the same type as the tracker was used as a target.

The standardized gunnery run, diagramed in figure 5, involved an initial 50-mil offset, a straight tail chase for about 40 seconds, and a 2g or 3g left turn for about 40 seconds by the target airplane, which lost altitude as necessary to maintain airspeed. Turns were made in only one direction to eliminate variations due to torque effects. The tracker pilot was instructed to keep the gunsight pipper on the point of intersection of the horizontal and vertical stabilizers of the target airplane. The runs during which 2g turns were made were started at a range of 1200 feet, while the runs which included 3g turns were started at a range of 800 feet so as to provide approximately the same ratio (about 0.5) of initial range to target turn radius R_o/r_t. This ratio was chosen on the basis of preliminary studies to eliminate large decreases in range and large increases in tracker normal acceleration in the turns, resulting from high initial ranges.

Additional tests in which the attacker airplane tracked the target in a series of turn reversals were made to determine whether or not increased evasive action would reveal any significant effects of lateral-oscillatory characteristics on tracking performance. The target airplane made four level 3g turn reversals at 10-second intervals and the standard deviation of tracking error in yaw and pitch was computed from film records over the entire run.

Rough-Air Simulation

The tracking runs were made both in smooth air and in simulated rough air to investigate the effects of variations in the lateral-oscillatory characteristics on tracking performance in the presence of an external disturbance.

The rough-air simulation conditions were established by first flying the airplane through a region containing moderately rough air and recording the controls-fixed airplane response in yawing and rolling velocity for configurations 1, 2, 3, and 4, defined in table I. Then on successive flights in smooth air the aileron and rudder disturbance amplitudes of the rough-air device were adjusted to reproduce approximately the standard deviation of $\dot{\psi}$ and φ responses of each configuration to natural rough air. The cam speed was chosen to provide similar distribution of energy (expressed by power spectral densities of controls-fixed yawing- and rolling-velocity response) with frequency in simulated and natural rough air, as shown for configurations 3 and 4 in figure 6. A presentation of the power-spectral-density concept applied to atmospheric turbulence may be found in reference 8.

Pilots

The smooth-air tracking performance of two pilots was evaluated separately. Pilot A was highly experienced in air-to-air gunnery and he was thoroughly familiar with the variable-stability test airplane. Pilot B was experienced in air-to-air gunnery but he was relatively inexperienced with the variable-stability airplane. Two factors minimized the effects of learning. First, the pilots were instructed to make two practice runs with each configuration before taking records and, second, both pilots had become familiar with tracking in this type of maneuver during other recent tracking-performance investigations (ref. 2).

Data Reduction

The tracking errors in yaw and pitch were read on every third frame from the projected image of the 16-mm gun-camera picture and were plotted as functions of time, as in figure 7. The standard deviations of yaw and pitch tracking errors σ_x and σ_y in smooth and simulated rough air were computed for the steady-straight and steady-turning portions of the standardized run (determined from the normal-acceleration record of the tracker airplane).

The transition time T_{A_Z}, standard deviation of yaw tracking error σ_x, and bias error $\overline{x}$ were determined over that section of the standardized run during which the normal acceleration of the tracker airplane was changing from 1g to the 2g or 3g steady-state value. These quantities, which were computed for the smooth-air runs, are listed in table II. Values of integrated-square error $\int_0^{T_{A_Z}} x^2 dt$ and mean-square error $\frac{1}{T_{A_Z}} \int_0^{T_{A_Z}} x^2 dt$, criteria of system effectiveness which may be applied to runs where significant transition bias errors are measured, were computed during T_{A_Z} and are also presented in table II.

Tracking data for the initial entry to straight level flight were not analyzed.

RESULTS AND DISCUSSION

Smooth-Air Tracking Performance

Steady-straight and steady-turning flight.- The effects of period, damping, and roll coupling on the standard deviation of yaw and pitch tracking errors in steady-straight flight and in steady turns in smooth air are presented in figure 8. Since changes in oscillatory characteristics in the lateral case are considered, only their effects on yaw tracking error are discussed.

For both pilots, the average values of standard deviation of yaw tracking error σ_x measured in smooth air were small, increasing somewhat with normal acceleration. Average values of σ_x for both pilots in straight flight and in steady 2g and 3g turns are given in table I, together with the lateral-oscillatory characteristics of all five configurations tested. On examination of figure 8 and table I, it is seen that period P and roll coupling $|\varphi|/|v_e|$ had negligible effects on σ_x. For pilot A, there appears to be a small favorable effect of increased damping $1/C_{1/2}$ on σ_x, particularly in the short-period configuration ($P = 2.3$ sec). However, the values of σ_x (from 1.2 to 3.6 mils) measured for all configurations were approximately at the lower limit of the range of values typical of modern fighter-type airplanes. This range is given in reference 2 and in table I of reference 9 as 2 to 5 mils. In addition, the standard deviation of angular dispersion for most gun-mount-ammunition combinations is from 2 to 4 mils (ref. 9), which is equal to or larger than the average values of standard deviation of yaw tracking error measured in this study. For these reasons, the differences in tracking performance measured over the range of lateral-oscillatory characteristics tested appear to have little significance, even though configurations 3, 4, and 5 were unsatisfactory and configurations 1 and 2 were satisfactory on the basis of pilots' opinions (figs. 3 and 4). These differences in tracking performance may become of greater importance should other factors affecting hit probability, especially the ballistic dispersion, be improved.

Transition phase.- Results of analysis of yaw tracking errors in the transition from straight flight to steady turns are presented in table II in the form of transition time T_{A_Z}, standard deviation of yaw tracking error σ_x, and tracking-error bias $\overline{x}$ during T_{A_Z}. These values include all five configurations in 2g and 3g turn entries with pilots A and B. Also given in table II are values of integrated-square error $\int_0^{T_{A_Z}} x^2 dt$ and mean-square error $\frac{1}{T_{A_Z}} \int_0^{T_{A_Z}} x^2 dt$, both in yaw.

An attempt was made to analyze the transition phase on the basis of the total transition time T_T, defined in reference 2 as

$$T_T = T_1 + T_{A_Z} + T_s$$

where T_1 is the time during which sighting disturbances are introduced due to initial rolling of the tracker before normal acceleration begins to change, T_{A_Z} is the time required for the normal acceleration of the tracker to increase from 1g to the steady-turn value, and T_s is the time after the tracker normal acceleration has reached its final value during which residual oscillations are present in the tracking error. However, the tracking-error time histories for the present study were generally of a nature which made the above definition impracticable. Attempts to determine visually the end of the transition phase yielded values of T_s which varied widely for the same configuration in similar turn entries. In most cases, the value of T_s for an individual run could not be found with reasonable assurance. Additionally, T_1 was found to be negligible (less than 0.5 sec). For these reasons the transition time used herein is T_{A_Z}, the time required for the normal acceleration of the tracker to increase from 1g to the steady-turn value. As would be expected, little change in T_{A_Z} occurred as the lateral-oscillatory characteristics were varied.

As seen in table II, the values of standard deviation of yaw tracking error σ_x computed during T_{A_Z} show no consistent trends with configuration; an occurrence which, on the surface, may be attributed to the somewhat arbitrary selection of T_{A_Z} as the transition period. In view of this, values of σ_x for each transition were computed during fixed periods which may be considered even more arbitrary than T_{A_Z}; namely, 5 seconds and 10 seconds from the beginning of T_{A_Z}. These values of σ_x are also presented in table II as evidence that in the present tests there were no consistent effects of changes in configuration on standard deviation of yaw tracking error during the transition phase, regardless of the transition interval chosen.

As shown in table II, no effect of configuration on the transition yaw bias error $\bar{x}$ is apparent. However, in most cases $\bar{x}$ was greater for the 3g target turn entries than for the 2g entries.

As stated in reference 2, standard deviation of tracking error serves as an adequate description of tracking performance during periods of steady normal acceleration and under conditions of changing normal acceleration where bias errors are negligible. The integrated-square error $\int_0^{T_{A_Z}} x^2dt$ and mean-square error $\frac{1}{T_{A_Z}}\int_0^{T_{A_Z}} x^2dt$ are given in reference 10 as criteria of system effectiveness which may be applied to cases where significant transition bias errors are measured. No conclusions regarding the values of $\int_0^{T_{A_Z}} x^2dt$ and $\frac{1}{T_{A_Z}}\int_0^{T_{A_Z}} x^2dt$ given in table II are felt to be warranted in view of the limited amount of data presented. Since no large or consistent effects of lateral period, damping, or roll coupling on tracking performance during the transition phase were revealed, it was not considered worthwhile to conduct further flight tests of this type for the purpose of gathering additional data.

Target turn-reversal maneuver.- In order to determine whether or not increased evasive action would reveal significant differences in tracking performance due to changes in the lateral-oscillatory characteristics, additional flights were made in which the attacker (pilot A) tracked the target airplane in a series of rapid turn reversals. The results of tracking during this maneuver are presented in figure 9, where values of standard deviation of yaw tracking error σ_x are given as functions of period P, damping $1/C_{1/2}$, and roll coupling $|\varphi|/|v_e|$. Configuration 1 ($P = 2.3$ sec, $1/C_{1/2} = 2.1$) shows a small improvement in tracking performance but otherwise there is no apparent effect of configuration on tracking in this maneuver.

Difficulty was found keeping the time between turn reversals and the normal-acceleration increase in the turns constant for all runs. Therefore, the ratio of the average change in normal acceleration ΔA_{Z_a} of the tracker to the average time τ between reversals for each run was used as a criterion of severity of the evasive maneuver. A tracker normal-acceleration time history typical of these maneuvers is presented in figure 10, indicating the method used to determine ΔA_{Z_a} and τ.

The effect of the ratio $\Delta A_{Z_a}/\tau$ on standard deviation of yaw tracking error σ_x for this type of run is presented for configuration 4 in figure 11. In order to eliminate effects on tracking error of large changes in severity of the target maneuver, runs where $\Delta A_{Z_a}/\tau$ differed by more than 25 percent from the value 0.20 (turns reversed at 10-sec intervals with $\Delta A_{Z_a} = 2g$) were not included in the data presented in figure 9. The variation of σ_x with $\Delta A_{Z_a}/\tau$ in figure 11, when compared with the variations of σ_x shown in figure 9, indicates that the degree of evasive activity had a much greater effect on tracking than did differences in lateral-oscillatory characteristics of the tracker airplane.

These results offer further evidence that, as for the transition phase of the standardized maneuver, variations in the lateral-oscillatory behavior over the ranges investigated in this study have no serious effects on tracking performance under conditions of rapidly changing normal acceleration.

Tracking Performance in Simulated Rough Air

Rough air is frequently encountered during low-altitude operations, such as air-to-ground attacks, and was therefore considered in this study. The correlation between simulated and natural rough air has been described in the Flight Technique and Data Reduction section of this report.

The effects of variations in lateral-oscillatory characteristics on standard deviation of tracking error in yaw and pitch under simulated rough-air conditions in steady-straight and steady-turning flight are presented for pilot A in figure 12. It is seen that the effect of period on the standard deviation of azimuth tracking error σ_x was large at the low value of damping (average $1/C_{1/2} = 0.26$) and that variation of damping had a large effect on σ_x in the short-period configurations ($P = 2.3$ sec). The average value of σ_x for straight flight and 2g and 3g target turns was greatest (8.3 mils) for configuration 4 ($P = 2.3$, $1/C_{1/2} = 0.20$) and smallest (2.4 mils) for configuration 2 ($P = 4.5$, $1/C_{1/2} = 2.1$).

The effect of $|\varphi|/|v_e|$ on yaw tracking error was small. The average value of σ_x was large for both configurations 4 and 5 (8.3 mils at $|\varphi|/|v_e| = 0.21$ and 7.1 mils at $|\varphi|/|v_e| = 0.80$), due primarily to low damping and short period.

The relationships between standard deviation of yaw angle σ_ψ in controls-fixed simulated rough-air flight and σ_x while tracking in simulated rough air are presented for configurations 1, 2, 3, and 4 in table III. These relationships are shown also in figure 13, where average values of σ_x for 1g alone and for 1g, 2g, and 3g tracking are expressed as functions of σ_ψ. In both table III and figure 13, the tracking errors follow the trend shown by σ_ψ as the configuration is changed. Upon closer examination of figure 13, two significant relationships are revealed. First, changes in σ_x for a given value of period appear to be proportional to changes in σ_ψ with the smooth-air yaw tracking errors considered as minimum values which the pilot does not attempt to or is unable to reduce further; and, second, the effect of σ_ψ on σ_x was about twice as great at the short period as at the long period, indicating that the pilot's ability to reduce a given amplitude of rough-air response is greatly affected by the period. The amplitude of rough-air response expressed by σ_ψ is strongly affected by the damping; that is, σ_ψ increases as damping is reduced. The predominant effect of damping on amplitude of response to rough air is pointed out in reference 11, where further discussion of the effects of airplane lateral-stability characteristics on flight behavior in turbulent air may be found. In view of these relationships, it appears that the most effective means of attaining desirable rough-air tracking performance is to assure that the lateral oscillation is well damped, particularly at short periods.

CONCLUSIONS

Measurements of fixed-sight tracking performance were made in selected air-to-air gunnery maneuvers by use of a conventional propeller-driven fighter airplane, the lateral-oscillatory characteristics of which were varied over wide ranges (period P from 2.1 to 4.5 sec, damping $1/C_{1/2}$ from 0.20 to 2.1, and roll coupling $|\varphi|/|v_e|$ from 0.15 to 0.80 deg/ft/sec). From these tests, the following conclusions are drawn:

1. In smooth air, no significant differences in tracking performance, as measured by bias and standard deviation of the tracking error, were apparent in straight flight or steady turns as the lateral-oscillatory characteristics were varied. In all cases, standard deviation of azimuth tracking error was between 1.2 mils and 3.6 mils.

2. The tracking data obtained during the transition period between steady-straight flight and steady-turning flight in smooth air failed to indicate any consistent effect of lateral-oscillatory characteristics when analyzed by various methods. Results of additional tests in which the target airplane made repeated turn reversals tended to verify the conclusion that the lateral-oscillatory characteristics have little effect on tracking performance under conditions of changing normal acceleration.

3. In simulated rough air, standard deviation of tracking error in yaw σ_x increased as the lateral period and damping were reduced. For example, σ_x increased from 2.4 mils to 8.3 mils as period P and damping $1/C_{1/2}$ were varied from 4.5 to 2.3 seconds and from 2.1 to 0.20, respectively. It appears that desirable rough-air tracking performance can be attained most effectively by assuring that the lateral oscillation is well damped, particularly at short periods.

Ames Aeronautical Laboratory
National Advisory Committee for Aeronautics
Moffett Field, Calif., Aug. 7, 1953

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TABLE I.- CONTROLS-FIXED LATERAL-OSCILLATORY CHARACTERISTICS OF THE FIVE CONFIGURATIONS TESTED AND AVERAGE VALUES OF STANDARD DEVIATION OF YAW TRACKING ERROR IN SMOOTH AIR

Configuration	P, sec	$1/C_{1/2}$, per cycle	$\frac{\lvert\varphi\rvert}{\lvert v_e\rvert}$, $\frac{deg}{ft/sec}$	σ_X, mils[1]
1	2.3	2.1	0.15	1.7
2	4.5	2.1	0.24	1.8
3	4.5	0.31	0.23	2.0
4	2.3	0.20	0.21	2.1
5	2.1	0.20	0.80	2.2

[1]Average for pilots A and B; 1g, 2g, and 3g steady state.

TABLE III.- STANDARD DEVIATION OF CONTROLS-FIXED YAW ANGLE AND STANDARD DEVIATION OF STEADY-STATE YAW TRACKING ERROR FOR CONFIGURATIONS 1 THROUGH 4 IN SIMULATED ROUGH AIR

Configuration	$\sigma_{\psi_{1g}}$, mils	σ_x, mils	
		1g only	Average 1g, 2g, 3g
1	28	2.6	3.4
2	14	1.7	2.4
3	81	3.5	4.1
4	129	7.1	8.3

TABLE II.- SMOOTH-AIR TRACKING-PERFORMANCE CHARACTERISTICS OF THE FIVE CONFIGURATIONS DURING THE TRANSITION PHASE

Pilot	Configuration	A_{Z_t}, g's	T_{A_Z}, sec	σ_x, mils during T_{A_Z}	σ_x, mils 5 sec	σ_x, mils 10 sec	$\bar{x}$, mils	$\int_0^{T_{A_Z}} x^2 dt$, mils^2-sec	$\frac{1}{T_{A_Z}}\int_0^{T_{A_Z}} x^2 dt$ mils^2
A	1	2	9.1	3.5	4.2	3.4	-0.6	120.4	13.2
		3	10.5	3.7	4.9	3.7	1.3	167.5	16.0
	2	2	4.4	3.8	3.9	3.8	-0.4	133.8	30.4
		3	7.5	5.5	4.8	5.5	0.1	310.7	41.4
	3	2	11.5	5.0	5.6	4.3	-0.4	934.6	81.3
		3	5.3	3.2	3.3	3.2	-1.4	341.1	64.4
	4	2	11.9	2.3	2.7	2.3	-0.9	395.5	33.2
		3	8.3	5.4	6.6	4.9	1.4	1305.6	157.3
	5	2	10.6	2.4	2.2	2.4	0.7	384.6	36.3
		3	5.9	6.2	7.1	6.0	3.0	2010.5	340.8
B	1	2	6.1	3.4	3.4	2.8	1.3	77.7	12.7
		3	5.8	3.2	2.6	3.1	1.8	113.8	19.6
	2	2	5.2	2.6	2.6	2.4	0.0	45.8	8.8
		3	6.2	3.6	3.0	3.2	0.8	83.6	13.5
	3	2	5.5	3.7	3.8	3.3	-0.9	76.6	13.9
		3	7.6	4.8	3.3	4.3	1.6	194.6	25.6
	4	2	5.9	2.3	2.3	2.6	-0.6	33.2	5.6
		3	6.2	5.5	5.8	4.6	2.4	204.2	32.9
	5	2	5.7	4.2	3.5	3.9	0.3	126.2	22.1
		3	4.5	5.7	5.4	4.6	2.4	173.3	38.5

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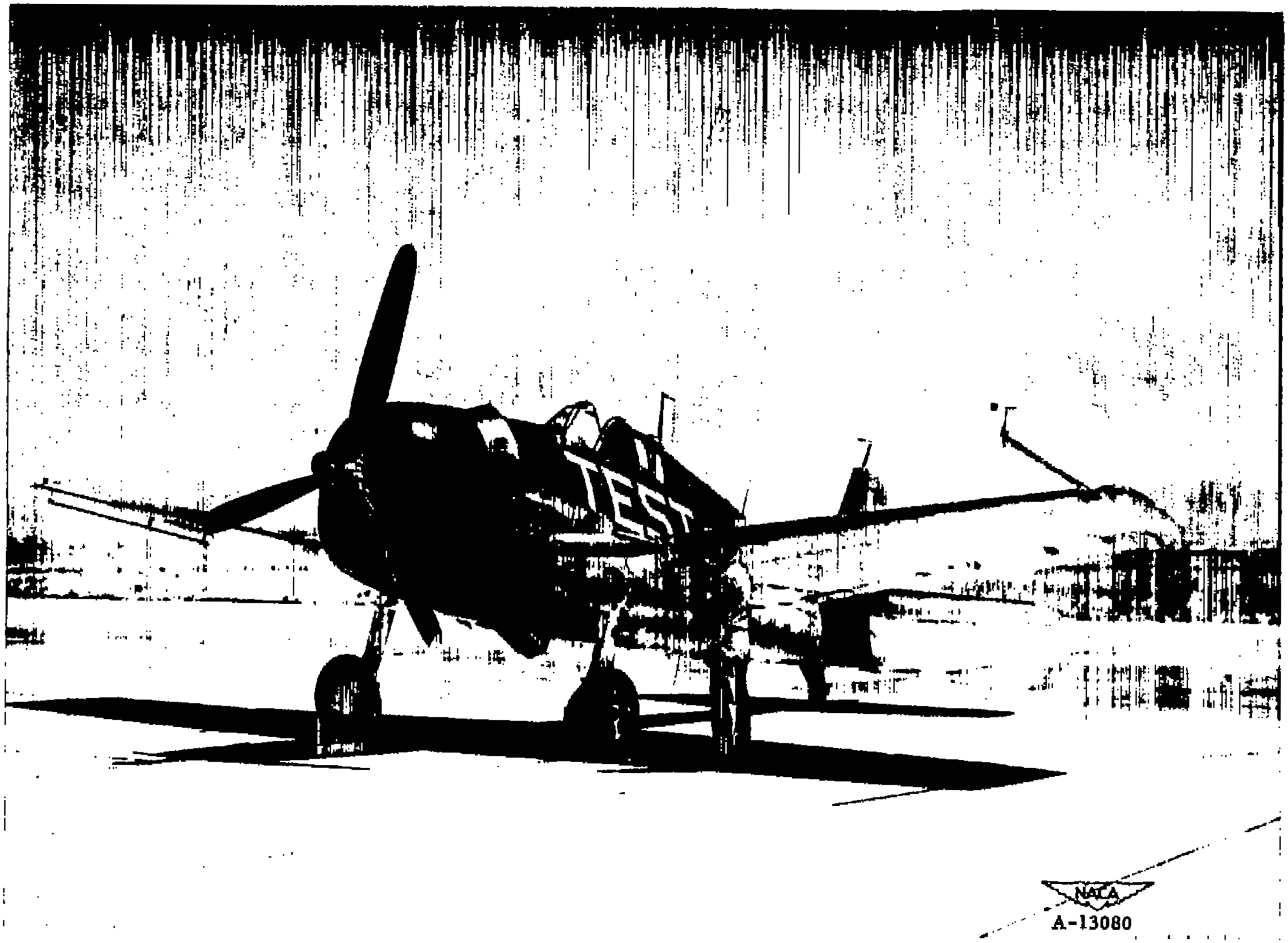


Figure 1.- Three-quarter front view of the tracker airplane.

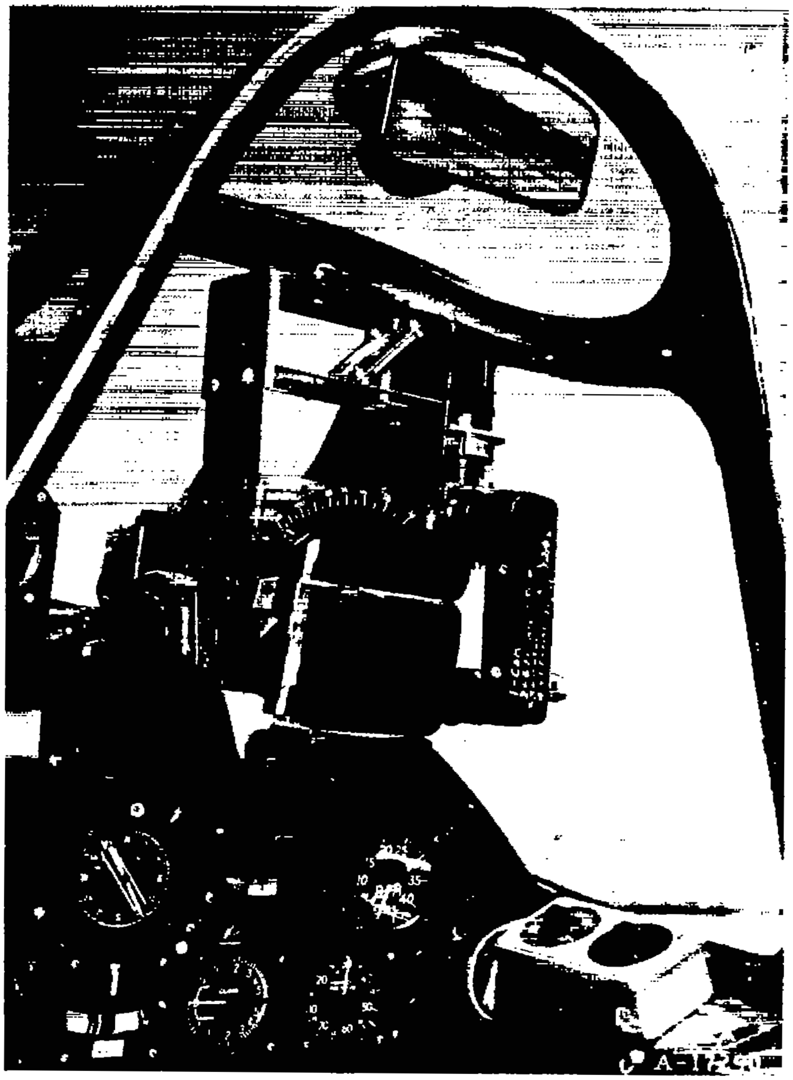


Figure 2.- Three-quarter rear view of gunsight and camera installation in cockpit of the tracker airplane.

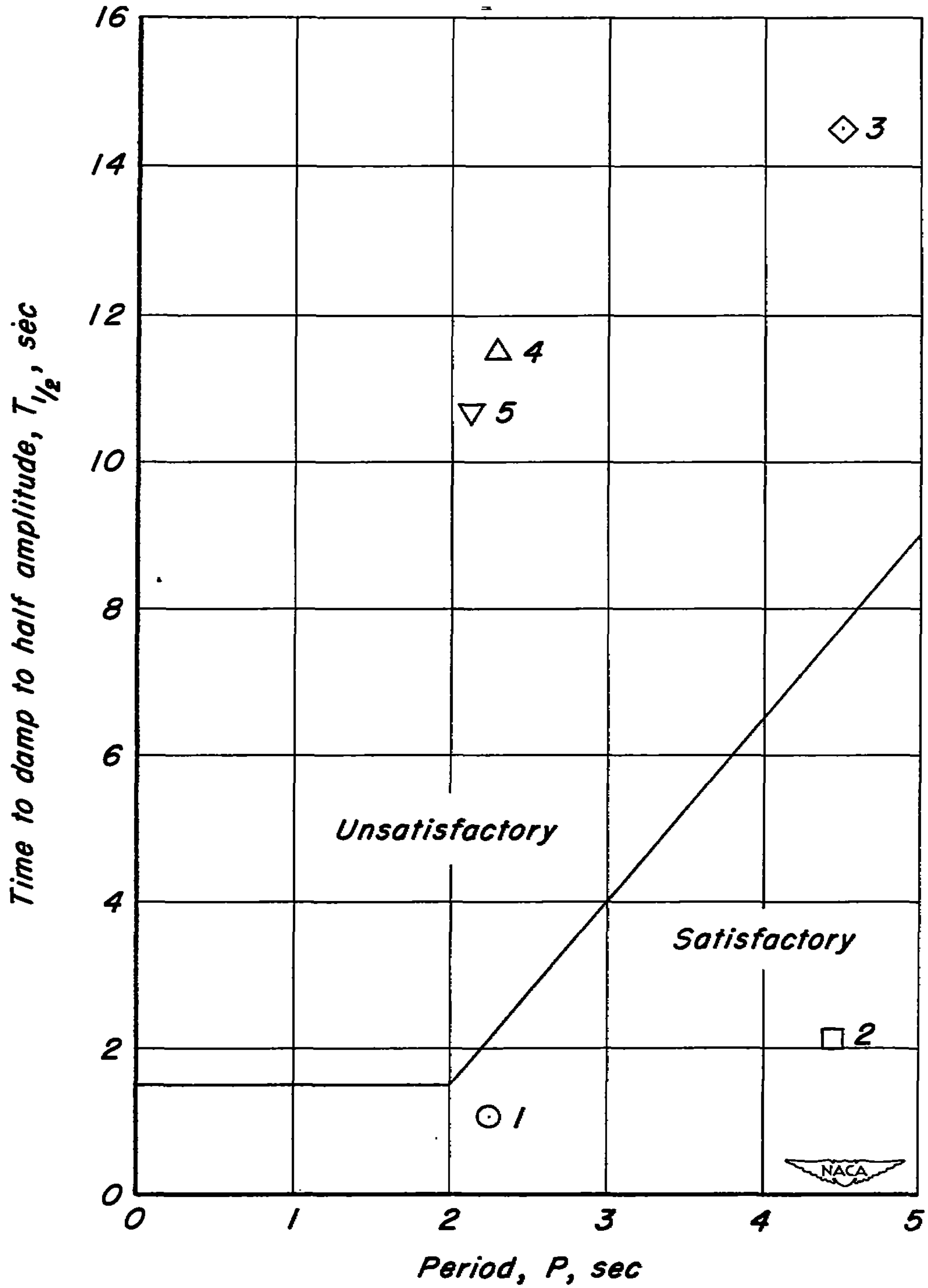


Figure 3.- Lateral-oscillation period-damping relationships of the five configurations tested compared with Armed Services specification (refs. 6 and 7).

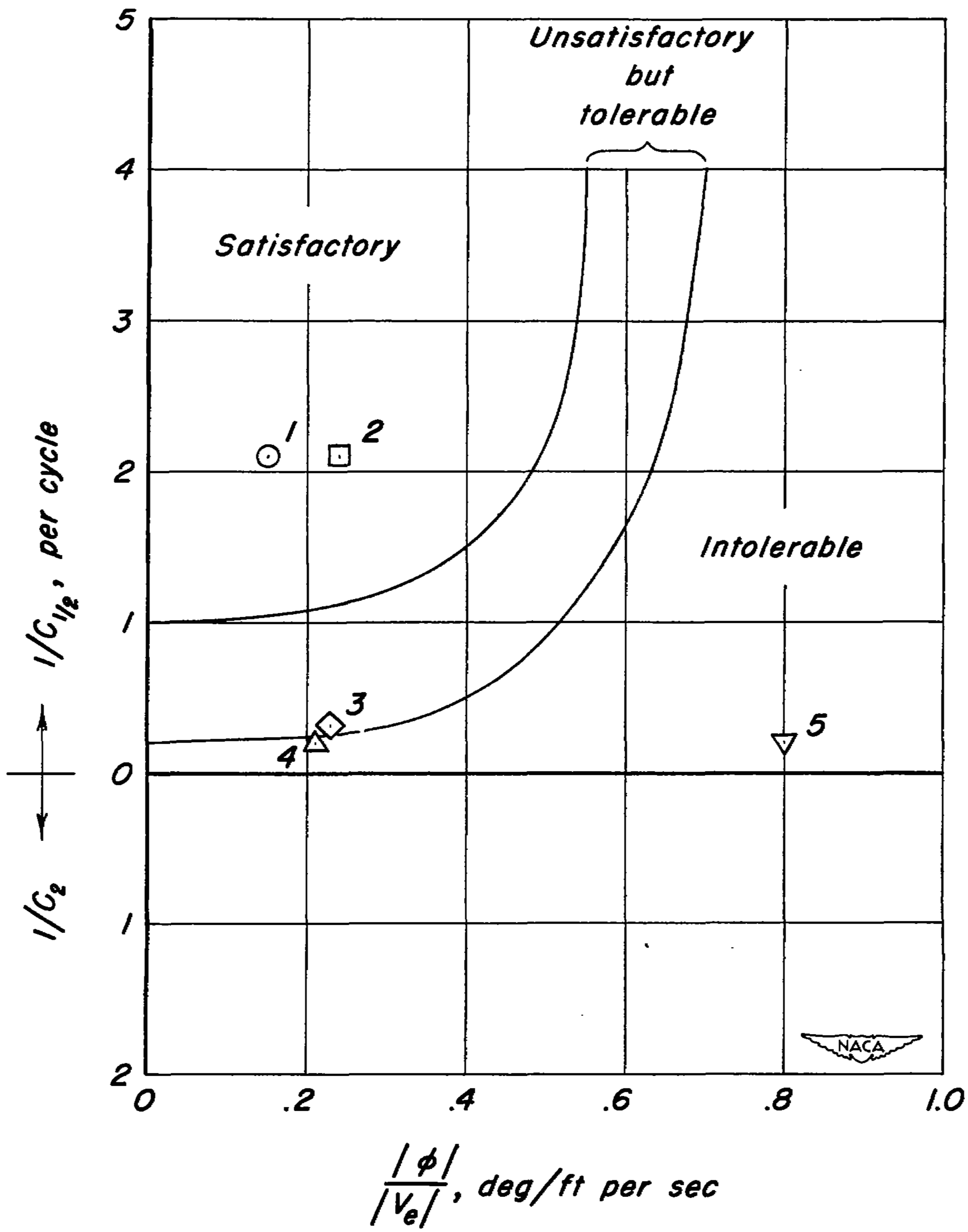
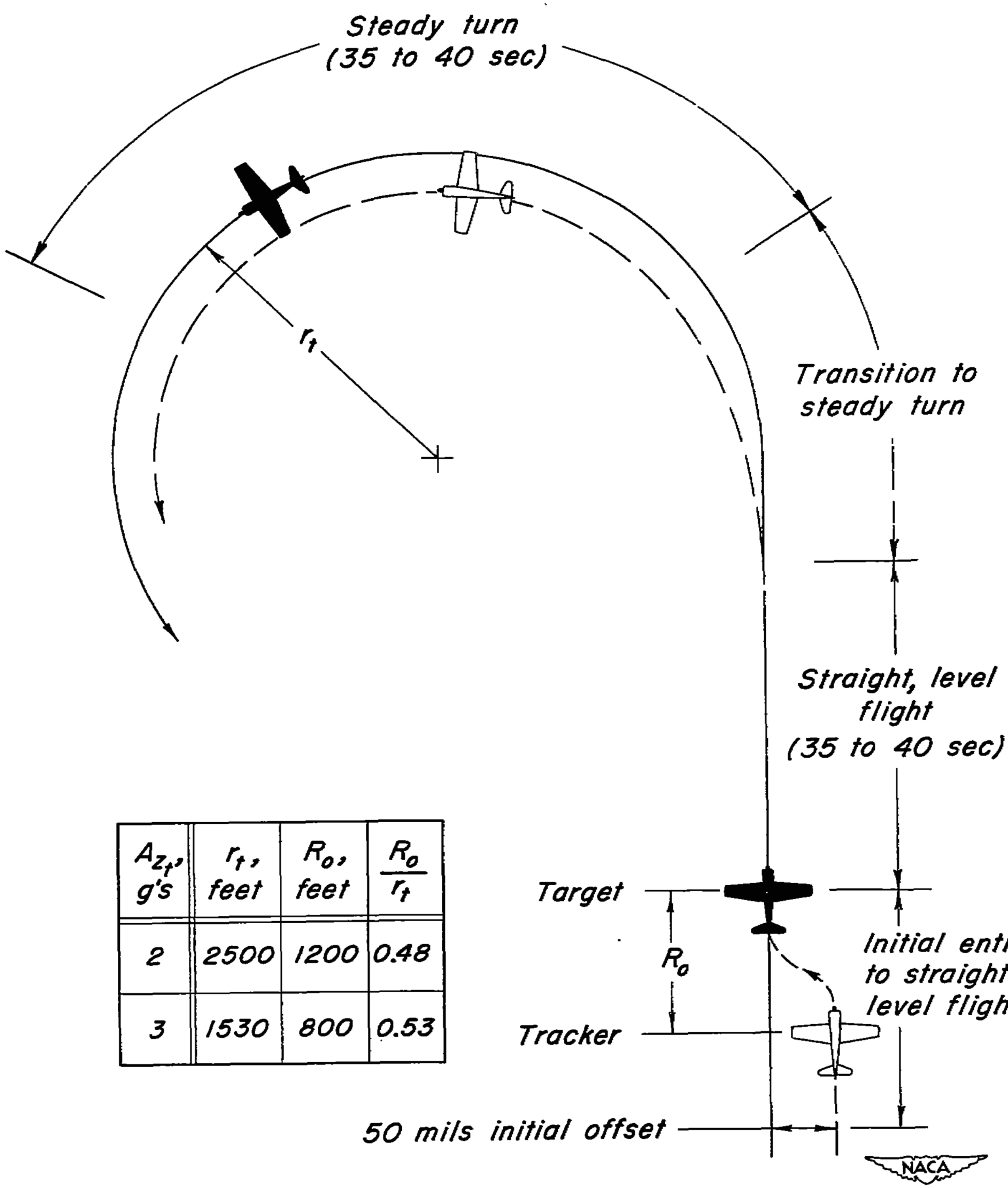
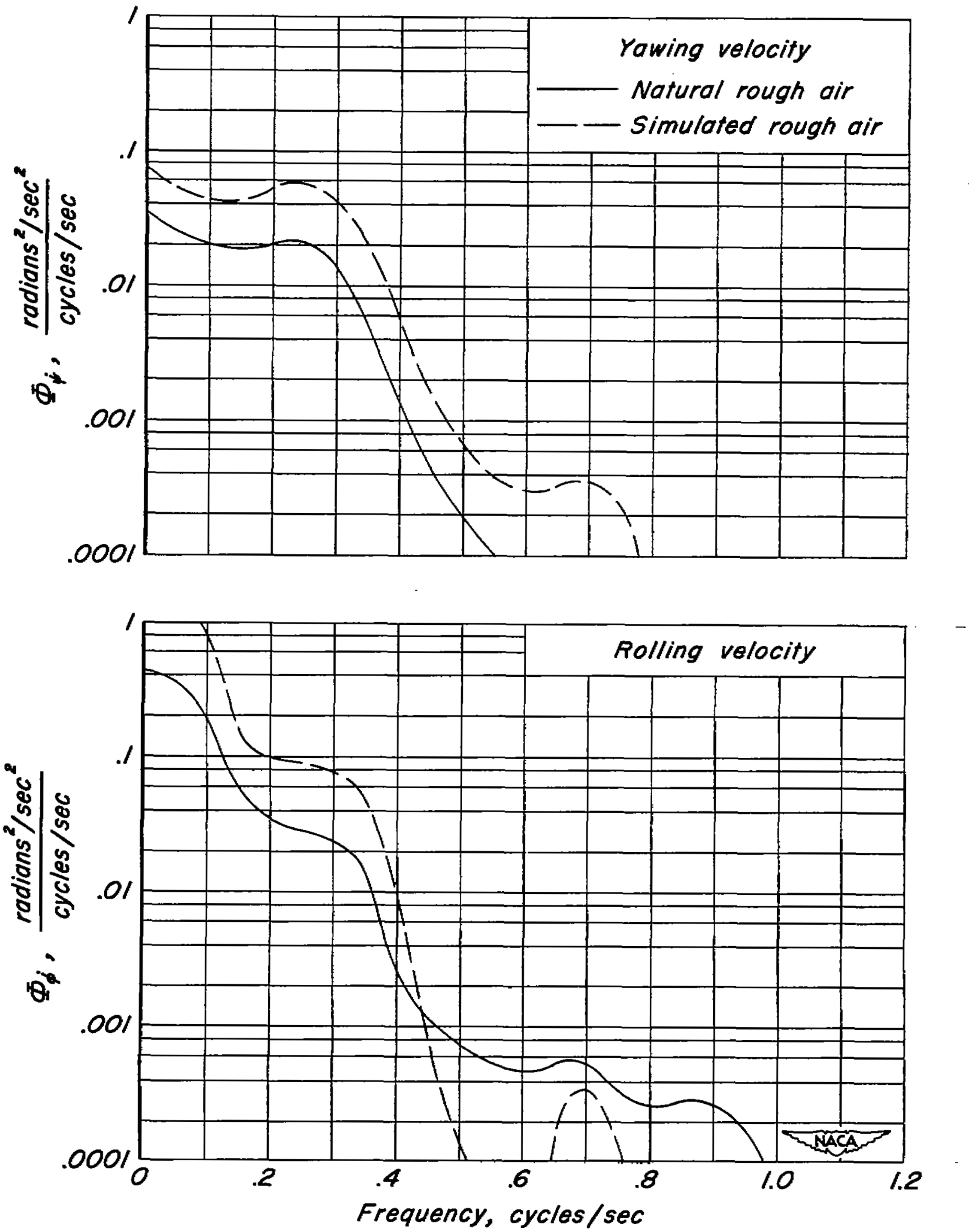


Figure 4.- Lateral-oscillatory characteristics of the five configurations tested compared with the pilot-opinion boundaries of reference 1.



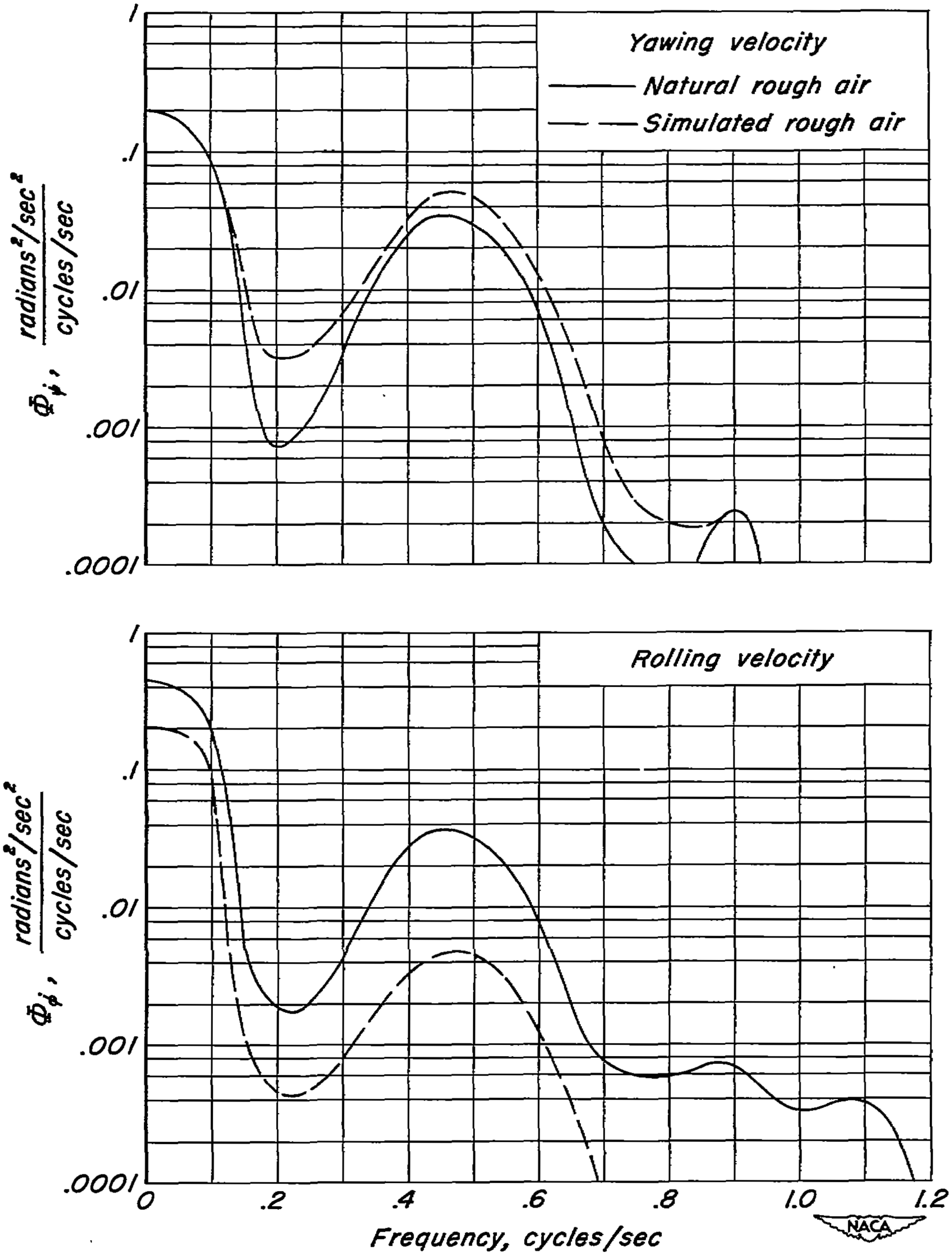
A_{z_t}, g's	r_t, feet	R_o, feet	$\frac{R_o}{r_t}$
2	2500	1200	0.48
3	1530	800	0.53

Figure 5.- Schematic diagram of flight paths flown during standardized gunnery run used in this study.



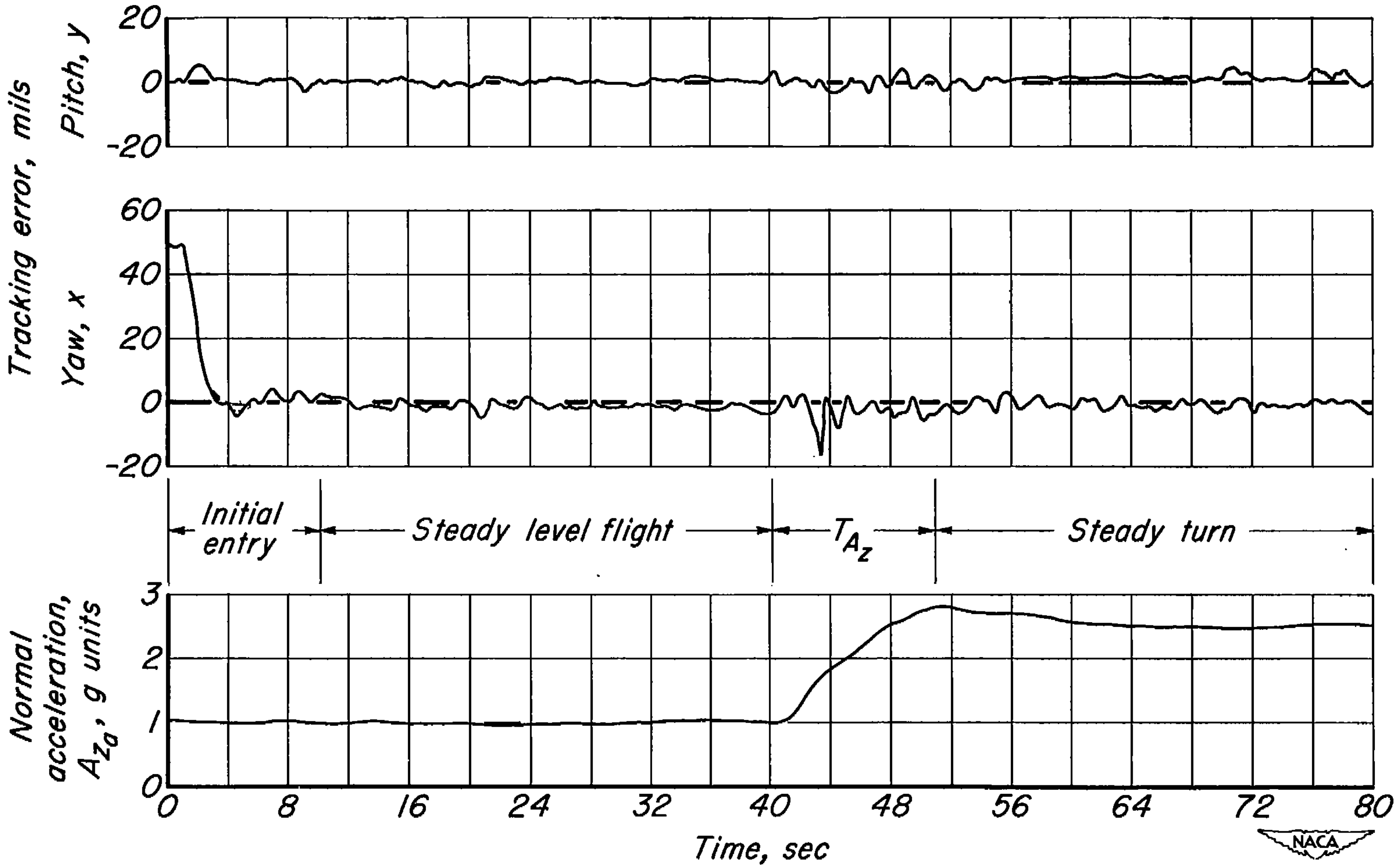
(a) Configuration 3 (P = 4.5).

Figure 6.- Power spectral densities of response of tracker airplane in natural and simulated rough air.



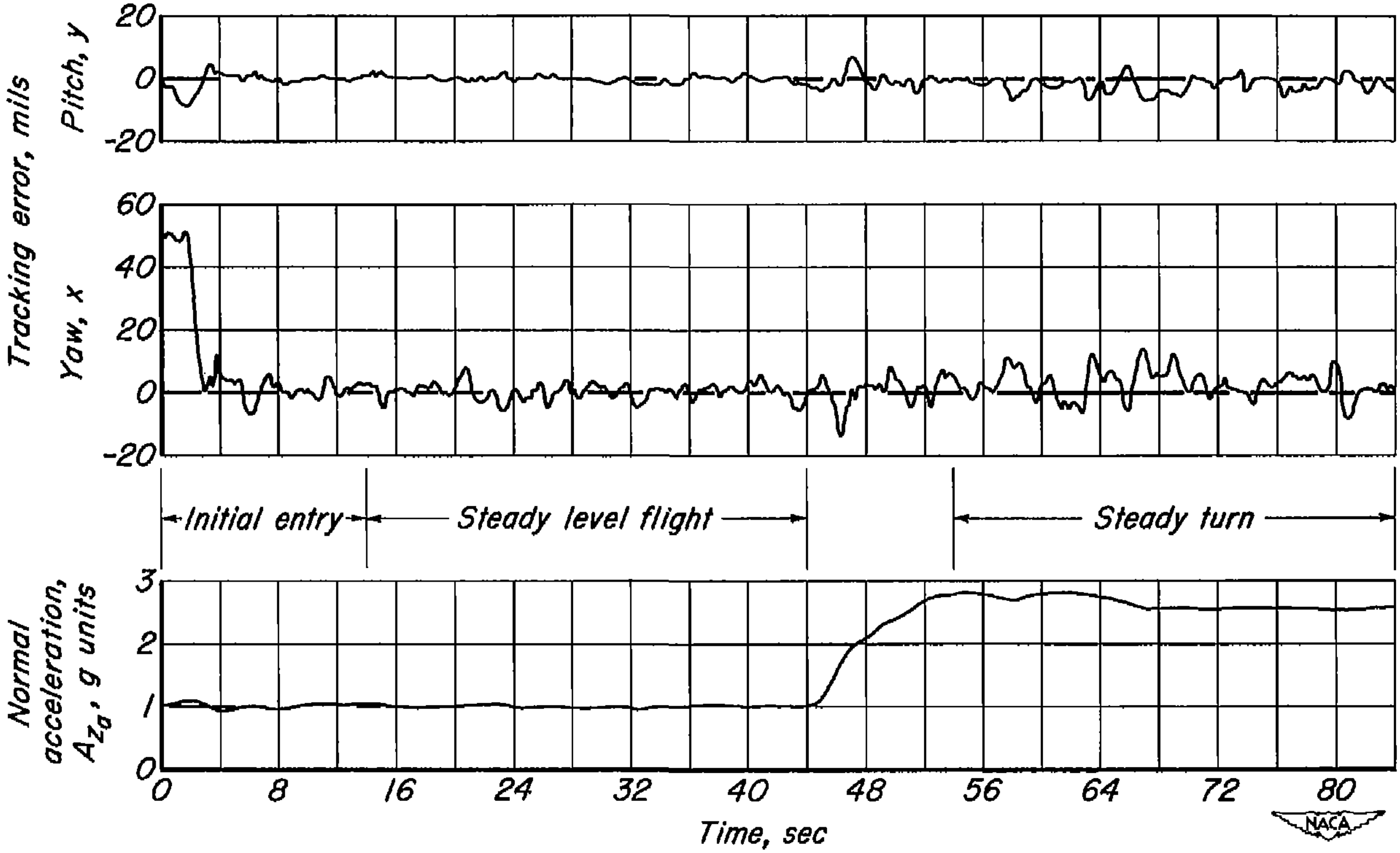
(b) Configuration 4 (P = 2.3).

Figure 6.- Concluded.



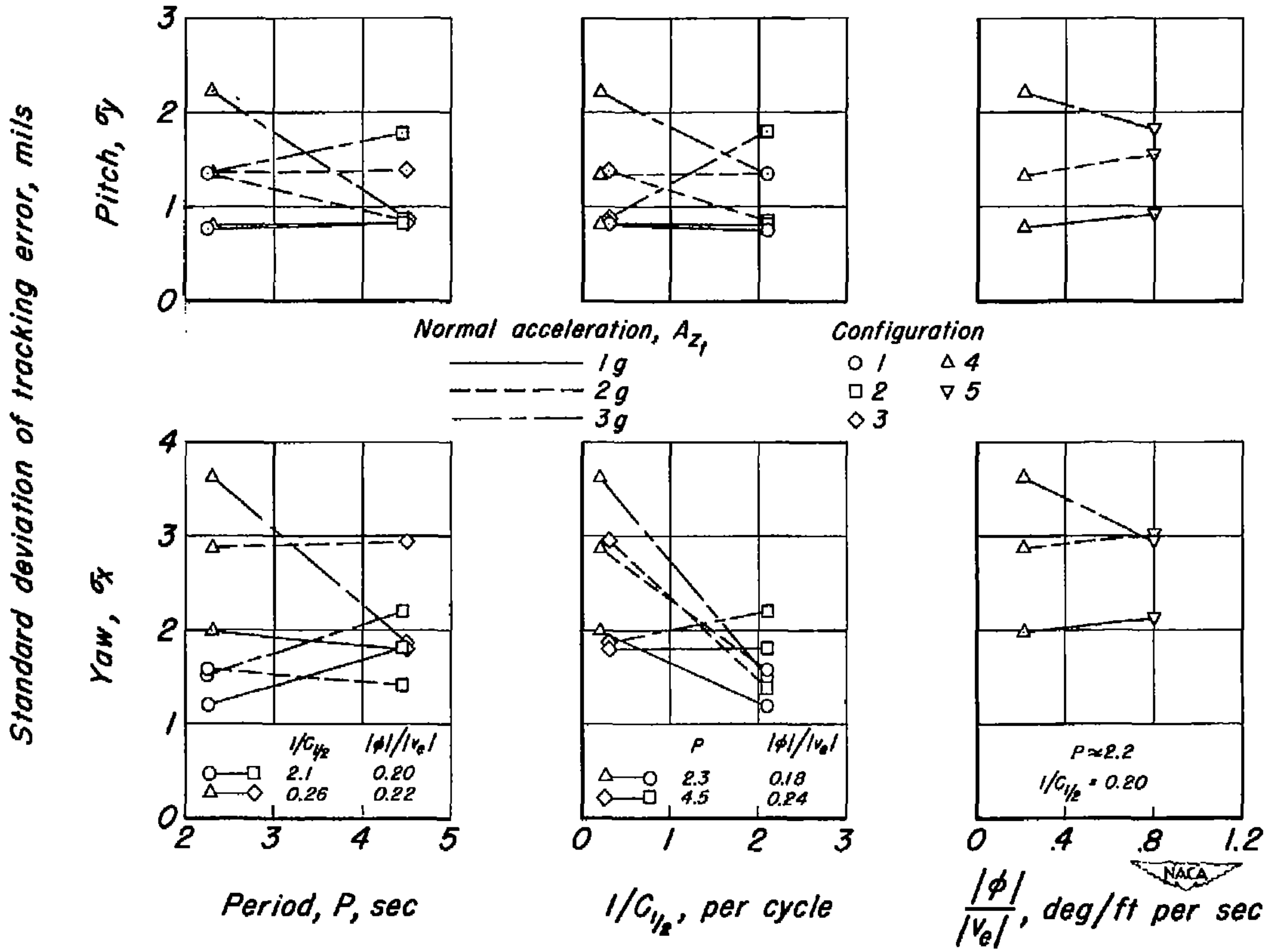
(a) Smooth air.

Figure 7.- Time histories of tracking error and tracker normal acceleration during a typical gunnery run. Configuration 1; pilot A.



(b) Simulated rough air.

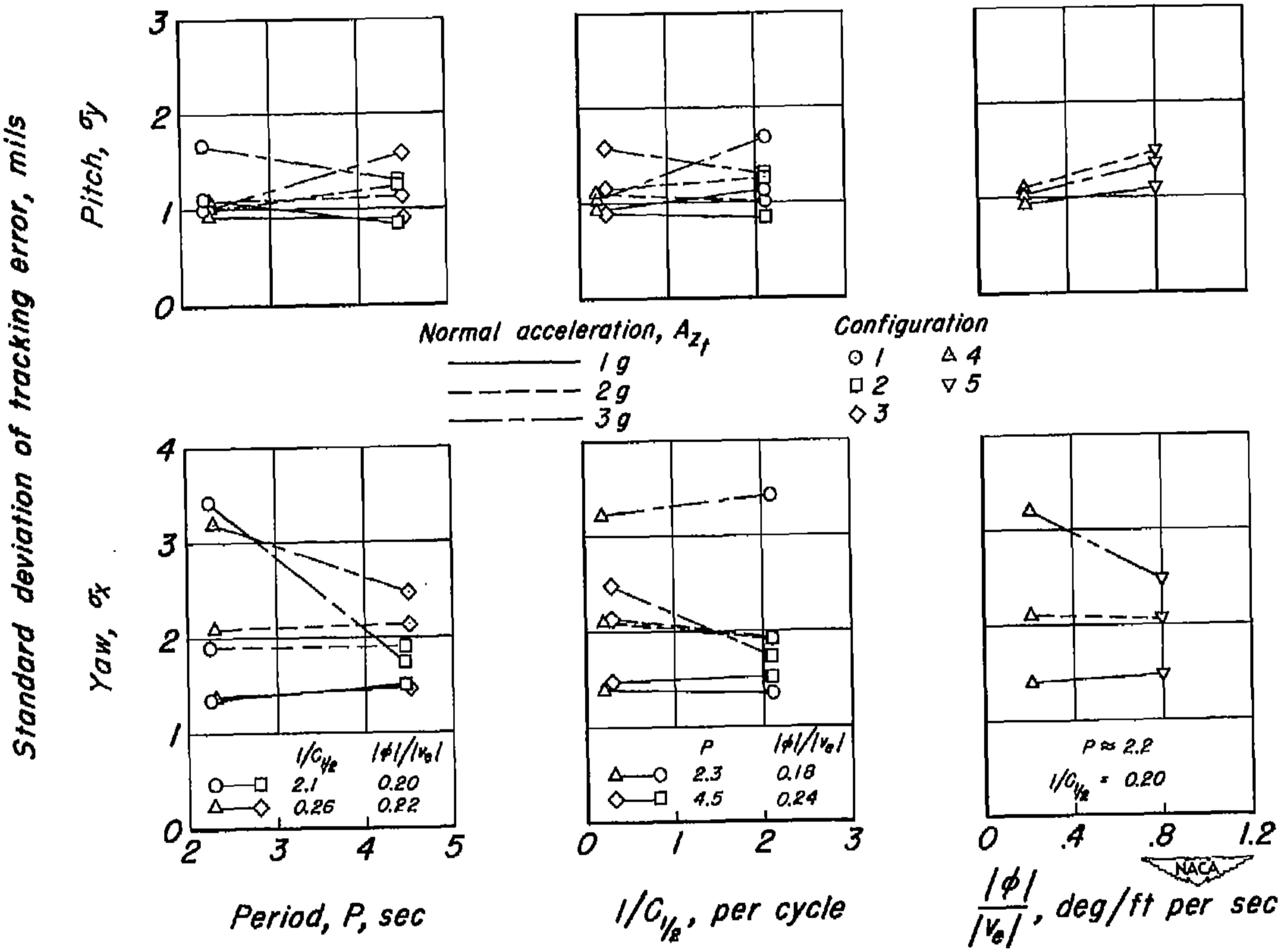
Figure 7.- Concluded.



(a) Pilot A.

Figure 8.- Variation of standard deviation of tracking error with lateral-oscillatory characteristics in steady-straight and steady-turning flight. Smooth air.

[redacted]



(b) Pilot B.

Figure 8.- Concluded.

[redacted]

[redacted]

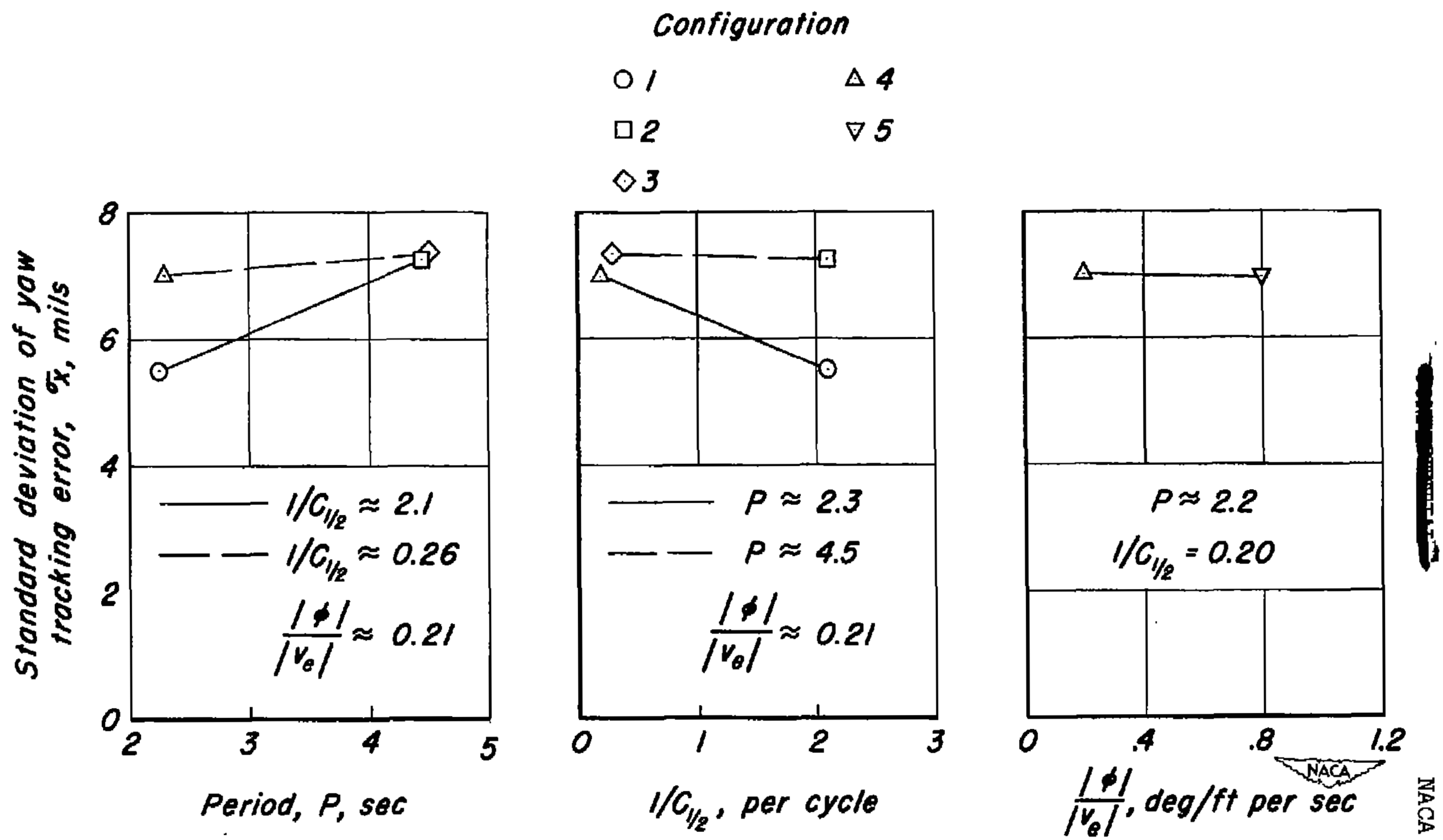


Figure 9.- Variation of standard deviation of yaw tracking error with lateral-oscillatory characteristics during target turn-reversal maneuver. Pilot A.

[redacted]

[redacted]

$$\Delta A_{z_a} = \frac{\Sigma \Delta A_{z_{a_i}}}{n} \qquad \Delta \tau = \frac{\Sigma \tau_i}{n}$$

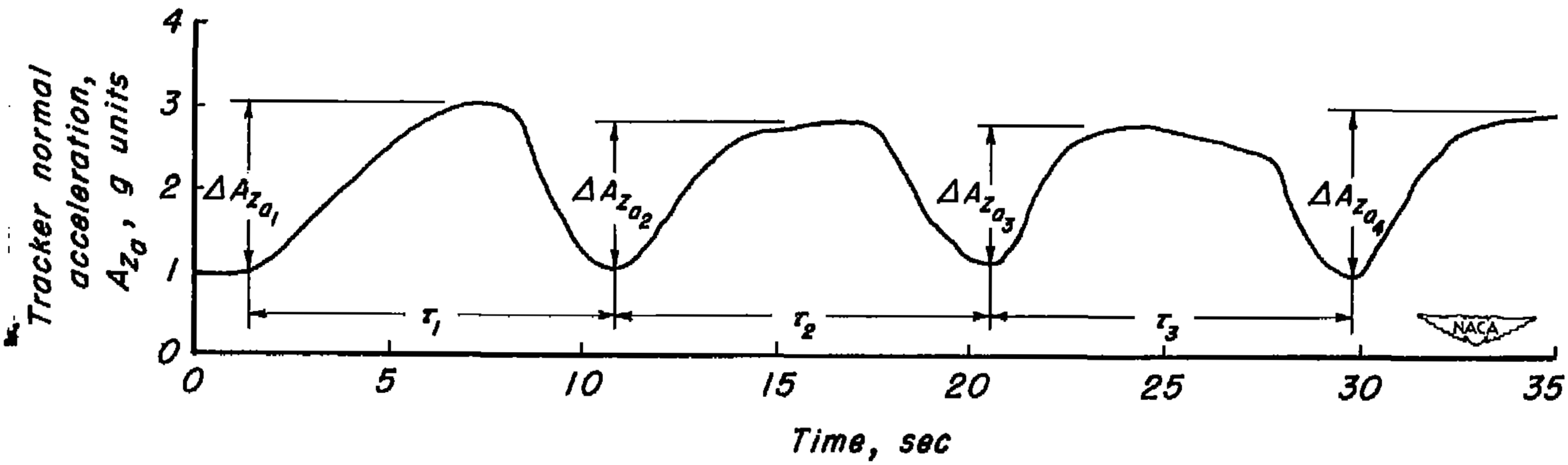


Figure 10.- Portion of a typical tracker normal-acceleration time history during target turn-reversal maneuver.

[redacted]

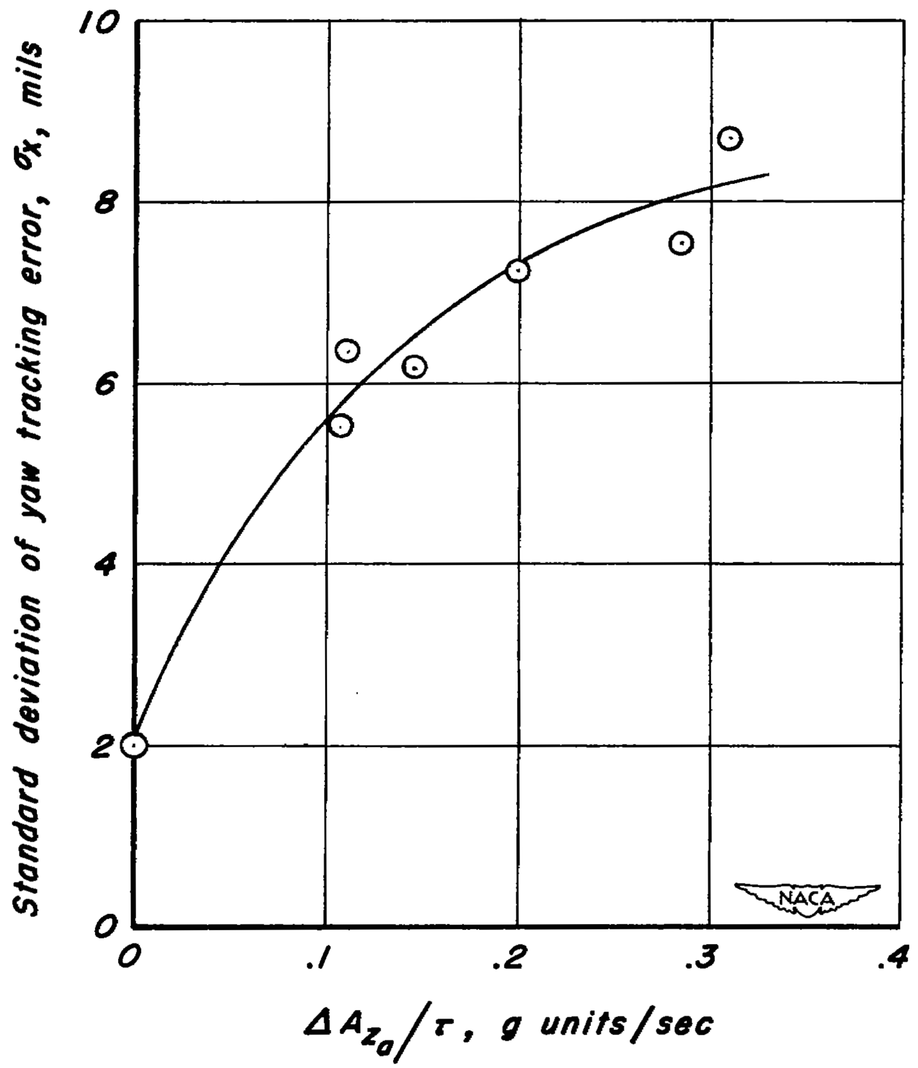


Figure 11.- Variation of standard deviation of yaw tracking error with target evasive action parameter. Configuration 4.

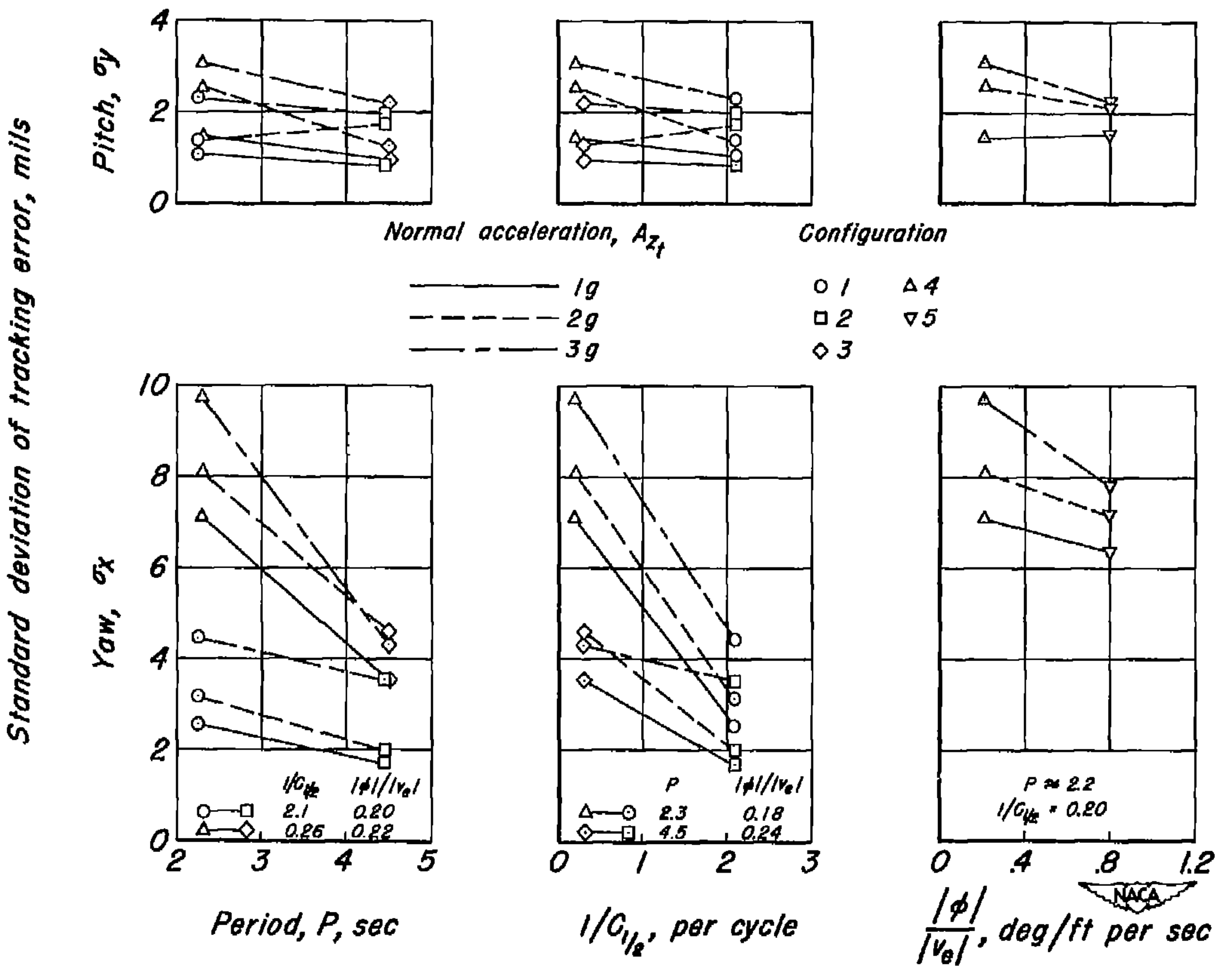


Figure 12.- Variation of standard deviation of tracking error with lateral-oscillatory characteristics in steady-straight and steady-turning flight. Simulated rough air; pilot A.

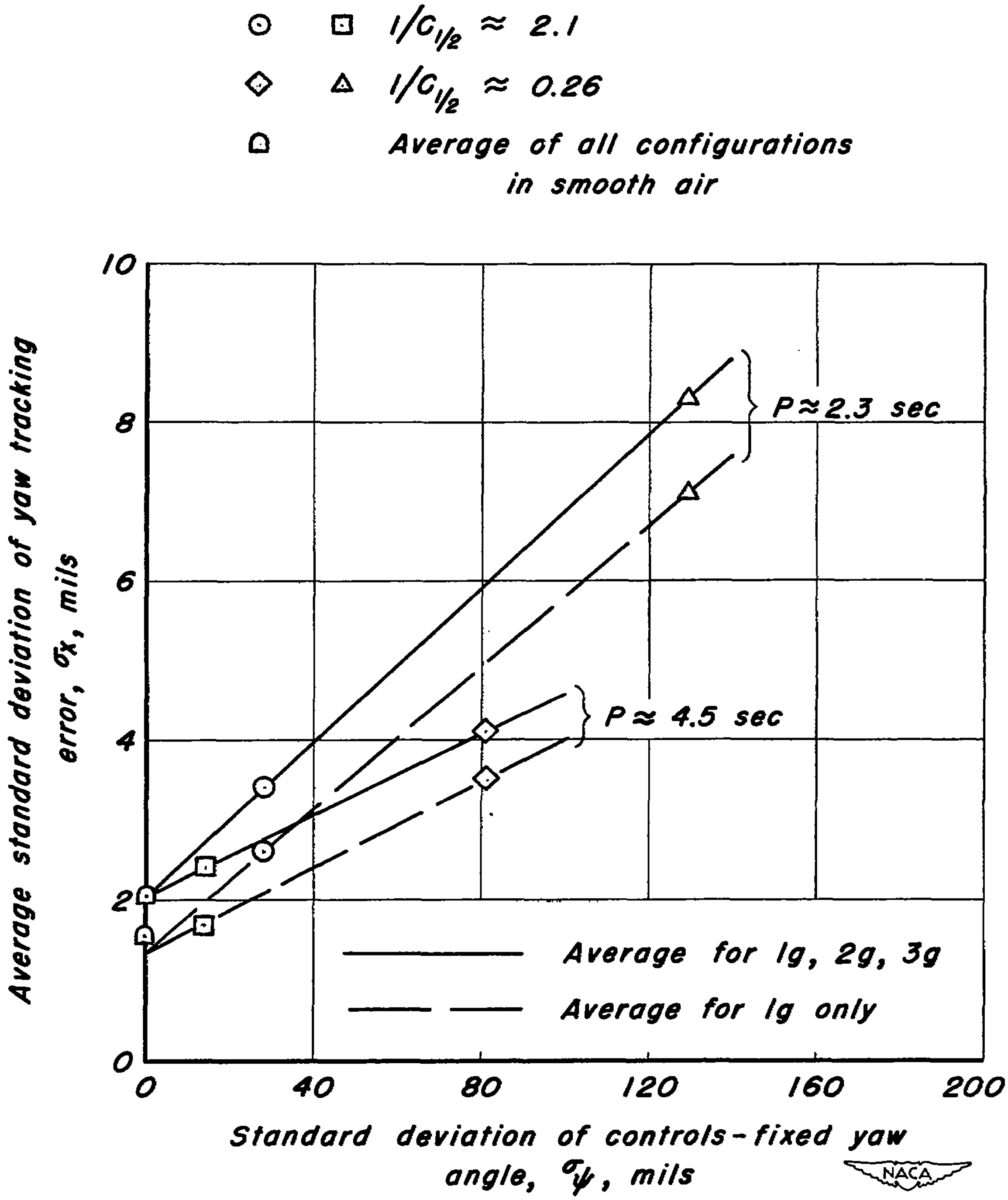


Figure 13.- Variation of average standard deviation of yaw tracking error with standard deviation of controls-fixed yaw angle in simulated rough air. Configurations 1, 2, 3, and 4; pilot A.

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